GEOTHERMAL ENERGY FROM HOT DRY ROCK: A RENEWABLE ENERGY TECHNOLOGY MOVING TOWARDS PRACTICAL IMPLEMENTATION

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ABSTRACT

The technology to extract useful amounts of energy from the large, ubiquitous, hot dry rock (HDR) resource has been under development for more than twenty years. Initial work during the 1970's and 1980's showed that it is possible to access and extract HDR energy using techniques originally conceived and tested by the Los Alamos National Laboratory. The process entails drilling a well deep enough to reach hot rock, injecting water at high enough pressure to open natural joints in the rock, and returning the water, heated by the rock, to the surface through one or more additional wellbores. After extraction of its thermal energy, the water is recirculated through the hot rock to mine more heat. In this closed-loop process, nothing is released to the environment except heat, and no long-term wastes accumulate.

The practical potential of HDR technology was demonstrated in a series of flow tests conducted from 1992 to 1995 at the HDR pilot facility at Fenton Hill, NM. These tests showed that energy can be extracted from HDR in significant amounts over extended time periods. Extensive analyses and reservoir characterization studies carried out as part of the testing program provided a large amount of information about the dynamics of the heat extraction process and confirmed that HDR energy production facilities can be operated with minimal environmental effects. Operating strategies evaluated during the test period included the production of energy at steady-state levels for extended periods and on a variable-output schedule particularly suited to load-following electricity generation.

KEY WORDS

Drilling, Energy Development, Flow Testing, Geothermal, HDR, Hot Dry Rock, Hydraulic Fracturing, Load Following, Reservoir

THE HDR RESOURCE

An abundant supply of energy exists virtually everywhere in the world in the form of geothermal heat in rock at depth. In a relatively few locations, mobile fluid naturally in contact with hot rock can be tapped to bring geothermal energy to the surface. These hydrothermal resources are already commercially exploited around the world, both to generate electricity and as direct sources of heat. By far the largest portion of the world's geothermal resources, however, reside in rock that is hot but is not naturally in contact with a fluid that can be used to transport that heat to the surface for use. The thermal energy content of such hot dry rock (HDR) found at accessible depths has been estimated to be on the order of 10 million quads (1 quad = 10^{15} BTU = 10^{15} Joules) (Edwards, *et al.*, 1982).

The quality of an HDR resource is determined primarily by the depth at which rock hot enough to provide energy at useful temperatures is found. This factor is, in turn, a function of the local geothermal gradient: the rate at which the earth's temperature increases with depth. Although the worldwide average geothermal gradient is 20-30°C/km, it may be as much as ten times higher in tectonically active regions (Otte, 1991). Areas with high geothermal gradients are found throughout the world. These provide sites for the early development and application of the technology to extract useful energy from HDR and, if commercially developed, could in themselves make HDR energy a major contributor to a clean-energy world in the 21st century. Low gradient areas are even more common. The exploitation of low-gradient HDR resources is presently not economically feasible because drilling to the great depths at which useful hot rock is found in these areas is extremely expensive. As the efficiency of extracting energy from HDR improves, it may be possible to provide all the energy needed for thermal and electrical processes almost everywhere from resources found right beneath our feet.

THE HDR ENERGY EXTRACTION PROCESS

All modern HDR development work is based on the relatively simple concept described in a US Patent issued to Los Alamos when HDR technology was more theory than reality (Potter, *et al.*, 1974). A well is first drilled into hot, crystalline rock. Water is then injected at pressures high enough to open the natural joints in the rock, thereby creating an engineered geothermal reservoir. The reservoir consists of a relatively small amount of water dispersed in a very large volume of hot rock. The relative dimensions and orientation of the reservoir are determined by the local geologic and stress conditions, while its ultimate volume is a function of the duration of the hydraulic fracturing operation and the fracturing pressures applied. Seismic techniques are used to follow the growth of the reservoir, to assess its location, and to determine its approximate dimensions. Using the seismic data as a guide, one or more production wells are subsequently drilled into the engineered reservoir at some distance from the first well. In a properly engineered HDR reservoir, there are a number of fluid-flow pathways between the injection and production wellbores.

Operation of an HDR heat mine is extremely simple. A high-pressure injection pump provides the sole motive force to circulate water through the engineered reservoir and deliver it to a power plant on the surface. The hydraulic pressure applied via the injection pump also serves to keep the joints within the reservoir propped open. The operating parameters applied to the injection pump thus greatly affect both the flow rate through the reservoir and its instantaneous fluid capacity. By using a combination of injection and production control measures, an almost limitless variety of operating scenarios may be employed to mine the heat.

HDR FACILITY DEVELOPMENT IN THE UNITED STATES

The world's first HDR heat mine was developed at Fenton Hill, NM, USA between 1974 and 1978. A small engineered geothermal reservoir was created by hydraulic fracturing in basement rock at a depth of about 3,000 m at a temperature of about 185°C. From 1978 to 1980, several experiments were conducted in which water was circulated through the reservoir (Dash, *et al.*, 1981). These tests proved conclusively that energy could be extracted from HDR by the process described in the Los Alamos patent.

Work on a much larger, hotter, and deeper HDR system was begun at Fenton Hill in 1980. After six years of drilling and fracturing, the second Fenton Hill HDR reservoir was finally completed. With an effective volume of about 20 million cubic meters, this new reservoir was estimated to be about 200 times larger than the first reservoir. It was centered at a depth of about 3,500 m in rock at temperatures of 220-240°C. Between 1987 and 1991 an automated surface plant was mated to the large reservoir. With the entire system in place, it was possible for the first time to conduct routine circulation through a large, hot, HDR reservoir that might serve as a prototype for a commercial HDR facility.

DEMONSTRATION FLOW TESTING DURING 1992-1995

Water was circulated through the large HDR reservoir for a total of about 11 months in a series of flow operations carried out from April 1992 thorough July 1995. Results from the three significant periods of steady-state circulation during this time are summarized in Table 1.

Table 1. Fenton Hill HDR Reservoir Flow Test Data

Test Period	Apr - July 1992	Feb. - Apr 1993	May - July 1995
Continuous Flow Period*, Days	112	56	65
Typical** Fluid Production Rate, l/s	5.68	5.86	6.57
Typical** Fluid Production Temp., °C	183	184	185
Water Loss Data			
Loss as % of Injected Volume	12	7	14
After a Continuous Flow Period of — Mo.	3.5	1.5	1.25
And a Continuous Pressurization Period of — Mo.	6	15	2

*Continuous Flow means production more than 95% of time period.
**Except at start up, production flow rates and temperatures were within 5% of indicated typical value.

The data of Table 1 illustrate the extremely reliable performance obtained during routine operation of the large Fenton Hill HDR system. During the interim of about 6 months between the first and second tests shown in the table, the reservoir was pressurized continuously, but circulation was maintained only about 50% of the time on an intermittent basis. Conversely, over the span of more than 2 years between the second and third tests, the pressure on the HDR reservoir was allowed to decline by more than 15 MPa to a level of about one-third of the circulation pressure. These two very different interim reservoir management strategies appeared to have essentially no effect on the productivity of the system during subsequent flow testing.

Water consumption in HDR reservoirs is largely the result of permeation of fluid from the pressurized joints into the micropores of the reservoir rock blocks, and the sealed joints and rock at the periphery of the reservoir. Water consumption therefore declines with time at any given pressure as these fluid sinks become saturated. This phenomenon is clearly evidenced in the water-loss data of Table 1, which show that water loss is directly related to the length of continuous reservoir pressurization rather than to the recent circulation history.

The flow tests of 1992-1995 also highlighted a number of other important characteristics of the large Fenton Hill HDR reservoir and, by implication, HDR reservoirs in general. Tracer tests conducted periodically during all three tests revealed the dynamic nature of the flow paths within the reservoir, with some flow paths closing and others developing as circulation proceeded, and overall fluid access to the hot reservoir rock increasing with time. The geochemistry of the fluid being continuously recirculated through the reservoir was consistently benign. Dissolved solids rapidly reached equilibrium levels of 3,000-4,000 ppm (about one-tenth the salinity of sea water) and remained within that range during all three test periods. Almost no suspended solids were brought to the surface. Low levels of dissolved gases, principally carbon dioxide, were contained in the circulating water, but no gaseous emissions to the atmosphere occurred during normal closed-loop operations of the HDR system.

In addition to the three steady-state flow tests summarized in Table 1, two important flow tests evaluated the potential for the operation of an HDR reservoir to meet time-variable energy demands (Brown, 1996). These tests showed that it is possible to increase the productivity of an HDR reservoir by as much as 60% within a period of about 2 minutes and to maintain that elevated level of production for at least 4 hours before rapidly reducing output back to the baseline level. This important result demonstrates the high degree of operational control that can be imposed on an engineered geothermal reservoir to provide a load-following power output.

CONCLUSIONS AND THE NEXT STEP IN HDR DEVELOPMENT

HDR is a vast energy resource found almost everywhere in the world. Research and development work conducted by the Los Alamos National Laboratory at the Fenton Hill, NM, HDR test site has taken the technology to extract useful energy from HDR from the conceptual stage through a concrete demonstration that useful amounts of energy can be routinely produced. Flow testing during 1992-1995 has shown that HDR systems are reliable and resilient. Operational flexibility that may provide a unique means of providing the energy needed to rapidly meet peaking or unanticipated power demands has been demonstrated.

HDR technology has been shown to be practical and versatile. Economic analyses have indicated the potential for HDR systems to produce energy at competitive costs (Tester and Herzog 1990). The next logical step in making HDR a viable energy resource is to develop an HDR system that will generate and market power, thereby providing the economic documentation that is needed to promote the rapid commercial application of this unique energy technology.

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